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II

A CONTRIBUTION TO THE CLIMATOLOGY OF THE ICE AGE[1]

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It is impossible to escape the conviction that in the early history of the earth its surface was hot. It was at one time a molten mass. The mean surface temperature of the earth where land is exposed now ranges from about zero degrees at the poles to about 80° Fahr. at the equator. Under the ocean, that is on three-fourths of the earth's surface, the temperature is about 35° to 40°. The mean temperature of the entire surface of the earth where not covered by water is generally given at about 55° to 60°.

On land areas there is a daily variation of ground temperature to a few feet in depth and an annual variation extending to depths of 20 to 50 feet, depending on the character of the composition of surface formations.

There is an increase in temperature with depth below the surface as shown by numerous temperature records in deep mines and in deep borings, as well as by the temperature of the water of deep flowing wells. This temperature increase, about 1° Fahr. in 40 to 60 feet, is of course quite variable, depending in large measure on the conductivity

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of the geologic formations. Should it continue at the average rate as ascertained for the limited depths which have been explored, the temperature at 25 to 30 miles below the surface would be high enough to fuse most rocks. There is, however, some evidence that the rate of temperature increase below the surface decreases somewhat with depth. Though this is a generally accepted conclusion there is, nevertheless, no good reason apparent for assuming that increase of temperature with depth does not continue to 100 miles or more below the surface.

Be this as it may, there is no dispute as to the fact of great internal heat and that the present low temperature of the surface of this globe is the result of cooling. There was a gradual and we may assume fairly unbroken transition from the condition of great heat to a condition of temperatures as we know them today.

May we not, then, indulge in a little speculation as to what, while the earth was thus cooling, was the condition of the water which now rests in the ocean beds at an average temperature of some 30° to 40°. For a time, water could exist in the form of vapor only. A little later, when surface temperatures approached the critical temperature of water, some water fell to earth but was again converted into steam as soon as it fell.

If we imagine the water of the oceans distributed over the entire surface of the earth at a uniform depth, it would represent a layer with an average thickness of about 10,000 feet. Preceding the time when the temperature of the earth had fallen to the critical temperature of water, that is, the temperature at which water can no longer exist as a liquid (about 689° Fahr.) the atmospheric pressure was about 300 times as great as at present. A vapor blanket denser than water at its critical temperature enveloped the earth.

When the cooling of the crust of the earth had progressed to, or a little below, the critical temperature of water, the atmospheric pressure was about 200 times as great as we now know it. At less pressure, water could not have existed as a liquid at this high temperature. One-third of the water was then liquid. Its density at that high temperature, 689° F. (365 C.) was only one-third as great as that of the water of our present ocean, consequently the one-third of the water which was liquid had a volume about equal to that of all the oceans of today, and the rest or two-thirds of the water was in the atmosphere as vapor. There was, moreover, no sudden change in the atmospheric pressure, while this change from dense vapor to water took place. Pressures everywhere remained the same during this transition because, in the depressions, hot water took the place of the hot vapor without change of volume. Thereafter, as cooling continued, more and more water was transferred from the atmosphere to the ocean and pressures on land areas became correspondingly less.

If all of the water could have been maintained in condensed form at its critical temperature of 689° Fahr., it would have covered the surface of the globe to an average depth of about 30,000 feet. On the assumption of the same inequalities in elevation of the earth's surface as today, the ocean surface would have been 20,000 feet higher than now and only the peaks of a few mountain ranges would have been above water. But, as already stated, two-thirds of the water was necessary as vapor to establish the pressure at which water can maintain itself as a liquid at its critical temperature. There was therefore no time at which the ocean could have had this extreme extent.

As the cooling progressed to temperatures lower than the critical temperature of water, the proportional amount of water in the air as water vapor decreased as already stated, and the density of ocean water increased at such relative rates that, in all probability, there never was any very great departure in the actual volume of ocean water from that of today, once the critical point in the cooling process had been passed. For a long time during this cooling process, heat was fed from below into the superimposed water producing convection and keeping the oceans warm, not cold as they are today, and of course accelerating evaporation.

The climate was hot and humid due to the preponderance of earth heat. It could not be otherwise.

The presence of water has always interfered with distribution of heat over the surface of the earth according to any uniform law. This was true of the period during which earth heat predominated even as at the present time. Unequal distribution of heat in those early periods must have caused violent movements in the atmosphere and here and there condensation of moisture on a scale beyond compare with anything of which we conceive as having occurred in recent geologic times.

From the conditions under preponderance of earth heat to the atmospheric conditions as we know them today, I venture to assume a gradual uninterrupted transition, already suggested, of which the great extent of glaciers in the Ice Age was but a temporary local phenomenon.

However, as temperature thus dropped, a period must have been passed through in which ocean water approximated present day temperatures at its surface, though still receiving enough heat from the warm ocean bed to cause more or less convection. It is to be assumed that ocean currents resulted in this transition period which were incomparably swifter and deeper than those with which we are familiar, and that these currents had a pronounced effect upon local climate and on the distribution of rainfall.

Under this conception of gradual cooling there is no place for the sudden arrival of a temporary era of cold as so generally assumed by geologists. The many ingenious explanations of such an era of cold appear to be somewhat superfluous.

Wherever in the writings on the Ice Age we turn to find an explanation of the conditions which then obtained we find ourselves confronted with attempts to account for a period of cold followed by a warmer climate, conditions which have been assumed essential to explain, first the extension of ice fields and second, their retreat. The widespread conception applied to the Northern Hemisphere has been, and still is, that of a period of cold coming down from the north followed by a moderation of climatic conditions with more sunshine, more rain and less snow, accompanied by a retreat of the ice northward.

Finding it necessary to offer some explanation for the assumed drop and subsequent rise in temperature of our northern latitudes, many have gone so far in this particular as to give serious consideration to cosmic causes such as suggested by Croll and ably discussed by numerous other geologists and physicists.

The precession of the equinoxes and secular changes in the eccentricity of the earth's orbit must, it is claimed, affect temperatures and may, therefore, account for the colder climate in the northern hemisphere during the Ice Age. It is claimed that in one-half of a cycle of 25,000 years, that is in 12,500 years from now we may expect another Ice Age. Our northern winters will be 22 days longer and 20 degrees colder, and our summers will be shorter, though much hotter than now. No one, however, who advances this cause of assumed, but not proved, recurrent ice ages, seems to have taken into account the obvious fact that a drop in the cold of winter in cold latitudes has little effect on the volume of accumulating snow, while a slight change in summer temperature has a relatively large effect on the rate of its melting and on the rate of evaporation; that, consequently, even less snow and ice is to be expected 12,500 years from now (in consequence of greater summer heat) when our northern summers and perihelion will occur at the same time, than at present with the earth in aphelion during our summer.

G. F. Becker (American Journal of Science, August, 1894) finds that in our temperate latitudes when the summer occurs at the time when the earth is at the point of its orbit nearest to the sun, the extreme summer temperature will be about 20° F. hotter than at present, and yet according to views frequently advanced, the longer colder winters are then to cause a great extension of glaciers.

In "The Age of the Earth" by Alphonse Berget (page 46) in discussing the exterior agencies which in the Quaternary

Era predominated in forming the earth's crust, and in speaking of the enormous precipitation of rain in that era the author says: "Snowfalls, prevented from melting by the fall in temperature, caused an enormous extension of the glaciers, which at that time covered the whole of Central Europe and all of North America."

The following is from a lecture by Professor Asa Gray delivered before Harvard University Natural History Society, April 18, 1878:

"North of our forest regions come the zones unwooded from the cold, the zone of arctic vegetation" . . . . "What would happen if a cold period were to come on from the north and were very slowly to carry the present arctic climate, or something like it, down far into the temperate zone? Why just what happened in the Glacial period, when the refrigeration somehow pushed all these plants before it down to Southern Europe, to Middle Asia, to the middle and southern part of the United States"; . . . . "Here then, we have reached a fair answer to the question how the same or similar species of our trees came to be dispersed over such widely separated continents. The lands all diverge from a polar center, and their proximate portions, however different from their present configuration and extent, and however changed at different times, were once the home of those trees, when they flourished in a temperate climate. The cold period which followed, and which doubtless came on in very slow degrees during ages of time, must long before its culmination have brought down to our latitudes, with the similar climate, the forest they possess now, or the ancestors of it."

And again, in speaking of the Miocene Tertiary or later deposits, Professor Gray says: "Geologists give the same name to these beds in Greenland and Southern Europe, because they contain the remains of identical or very similar species of plants; and they used to regard them as of the same age on account of this identity. But in fact this identity is good evidence that they can not be synchronous. The beds in the lower latitudes must be later, and were forming when Greenland probably had very nearly the same climate which it has now." . . . . "The Glacial period or refrigeration from the north, which at its inception forced the temperate flora into our latitude, at its culmination must have carried much or most of it quite beyond. To what extent displaced, and how far superseded by the vegetation which in our day borders the ice, or by ice itself, it is difficult to form more than general conjectures, so different and conflicting are the views of geologists upon the Glacial period. But upon any, or almost any, of these views it is safe to conclude that temperate vegetation, such as preceded the refrigeration, and has now again succeeded it, was either thrust out of northern Europe and the northern Atlantic States or was reduced to precarious existence and diminished forms. It also appears that, on our own continent, at least, a milder climate than the present, and a considerable submergence of land, transiently supervened at the north, to which the vegetation must have sensibly responded by a northward movement, from which it afterward receded."

Geikie in his Text book of Geology says (page 887): "Under the name of the Glacial Period or Ice Age, a remarkable geological episode in the history of the northern hemisphere is denoted. The Crag deposits afford evidence of a gradual refrigeration of climate at the close of Tertiary ages."

James D. Dana, discarding the effect of the changing eccentricity of the earth's orbit upon climate as a cause of the Ice Age, nevertheless admits, apparently, that there must have been a general lowering of the temperature to permit the spread of the ice. On page 979 of his Manual of Geology we read: "the amount to which the mean temperature of the globe was lowered to bring on the conditions of the Glacial period was probably small . . . " E. Bruckner, in a recent discussion of the subject, concludes that a change in mean temperature of 8° F. to 10° F. would be sufficient.

Louis Figuier in "The World before the Deluge," thus refers to the Ice Age: "The northern and central parts of

Europe, the vast countries which extend from Scandinavia to the Mediterranean and the Danube, were visited by a period of sudden and severe cold; the temperature of the polar regions seized them. The plains of Europe, but now ornamented by the luxurious vegetation developed by the heat of a burning climate . . . . became covered with a mantle of ice and snow."

The Ice Age occurred at the close of the Tertiary and beginning of the Quaternary geologic period. This was at a time when the life on the earth was not greatly at variance with life of our time. But the earth's surface was habitable, notably before the Ice Age, by animals and plants requiring a temperate or warm climate far to the northward of the points to which such climates now extend.

In the Tertiary Period there was a remarkable assemblage of animals on our continent, many species of which became extinct during the presence of the great ice sheet. Their remains are found in the post-Pliocene deposits. On this subject G. F. Wright in the "Ice Age in North America" says (page 387): "The program of events seems to have been about as follows: In the warm period preceding the Glacial epoch, when the vegetation of the temperate zone flourished about the North Pole, there was land connection between the continents, permitting the larger species of the Old World to migrate to North America. At the same time the conditions in North America were favorable to the tropical species of animals which had developed and flourished in South America. The refrigeration of the climate on the approach of the Glacial Period, and the advance of the ice from the north, cut off retreat to the Old World species and gradually hemmed them in over the southern portion of the continent, where all forms of life were compelled to readjust themselves to new conditions." . . . .

"With the withdrawal of ice to the north, the struggle of these animals with the conditions of existence began anew, and the mammoth and some others found themselves unable to cope with the changes to which they were compelled to adjust themselves. From the abundance of the remains of these animals found in the peat bogs of kettle holes in the glacial terraces of gravel and loess, it is evident that they followed close upon the retreating ice front, and some of them continued the retreat to the Arctic Circle, where they still live and flourish; while others like the elephant and mastodon, perished."

It should be added that the mammoth could live, under the mild climatic conditions of the Ice Age, so close to the margin of the ice, that occasionally one of them—probably in attempting to cross swamps at the sides or fringes of the glaciers—became entrapped and was conserved there in frozen condition even to the present day. Geologists tell us that many have been found with skin and hair and even the flesh well preserved. One such specimen of which there is record, was discovered in Northern Siberia at the mouth of the river Lena in 1806; another also in Northern Siberia in 1846 and another subsequent to the delivery of this paper in 1925 or 1926.

But it is not the purpose of this paper to discuss at length the general conditions on the surface of the earth during the Ice Age or the relative importance of changes in elevation of the glaciated regions and of changes in ocean currents which may have affected the extent of ice fields. Certain characteristics of the climate of the late Tertiary and Quaternary times, no doubt locally affected to some extent by the presence of the ice fields are, however, to be noted.

Let me now call attention to a feature of the Quaternary landscape which, like the glaciers has, due to a change in climate, disappeared. I refer to the Great Quaternary (or Pleistocene) lakes of the Lake Bonneville type. The largest of these, Lake Agassiz, owing to the fact that it was the ponded water at the southerly foot of the great North American ice field, should perhaps be put in a class by itself. But it, too, may be accepted as evidence of the fact that in its time there was abundant precipitation. The immediate concern will not be with this lake, however, but with the three, Lake Bonneville, Lake Lahontan and the ancient Lake Mono, all so well described by geologists of the U. S.

Geological Survey, notably Dr. G. K. Gilbert, I. C. Russell and Warren Upham.

The birth of the Sierra Nevada may, according to the geologists, be placed in the Tertiary Period of Geologic time. Preceding the cataclysm which resulted in its upheaval there had been vast deposits over the entire western portion of our continent from ocean water or under ocean water and when the shrinkage of the earth's crust and its folding came these were lifted to high altitudes. Then erosion set in. River systems were formed on a large scale many of which were destroyed in a later era, when there was further shrinkage and more crumpling of the earth's crust, with much escape of lava, giving a new aspect to the country. The great depression between the Sierra Nevada and the Coast Range began to fill up with detrital material washed down from the mountains.

It was after the uplift of the Sierra Nevada in the late Tertiary and in the Quaternary epoch that the lakes already referred to had their greatest extent. The interior saucer-shaped basin or valley at the lowest point of which we now find the Great Salt Lake of Utah, was filled in the early part of Quaternary times with water to an elevation 1000 feet higher than the present lake level. This great ancient lake to which geologists have given the name "Bonneville" had an extent of 19,750 square miles. For thousands of years, long enough to clearly mark an easily traceable beach line, evidenced in places by large deposits of gravel, this lake had no outlet; then it broke its barrier to the north and discharged toward Snake River, cutting its outlet, with occasional pauses in its descent, down into soft rim-rock about 370 feet. Thereafter for other thousands of years it maintained a fairly constant level at the height of this outlet about 625 to 630 feet above the present lake level.

Another such interior Pleistocene lake covered a large area in Nevada now occupied in small part by Pyramid and Winnemucca lakes and by the sinks of Humboldt and Carson rivers. This lake is known as Lahontan Lake. Its extent was a little less than one-half of that of Lake Bonne-

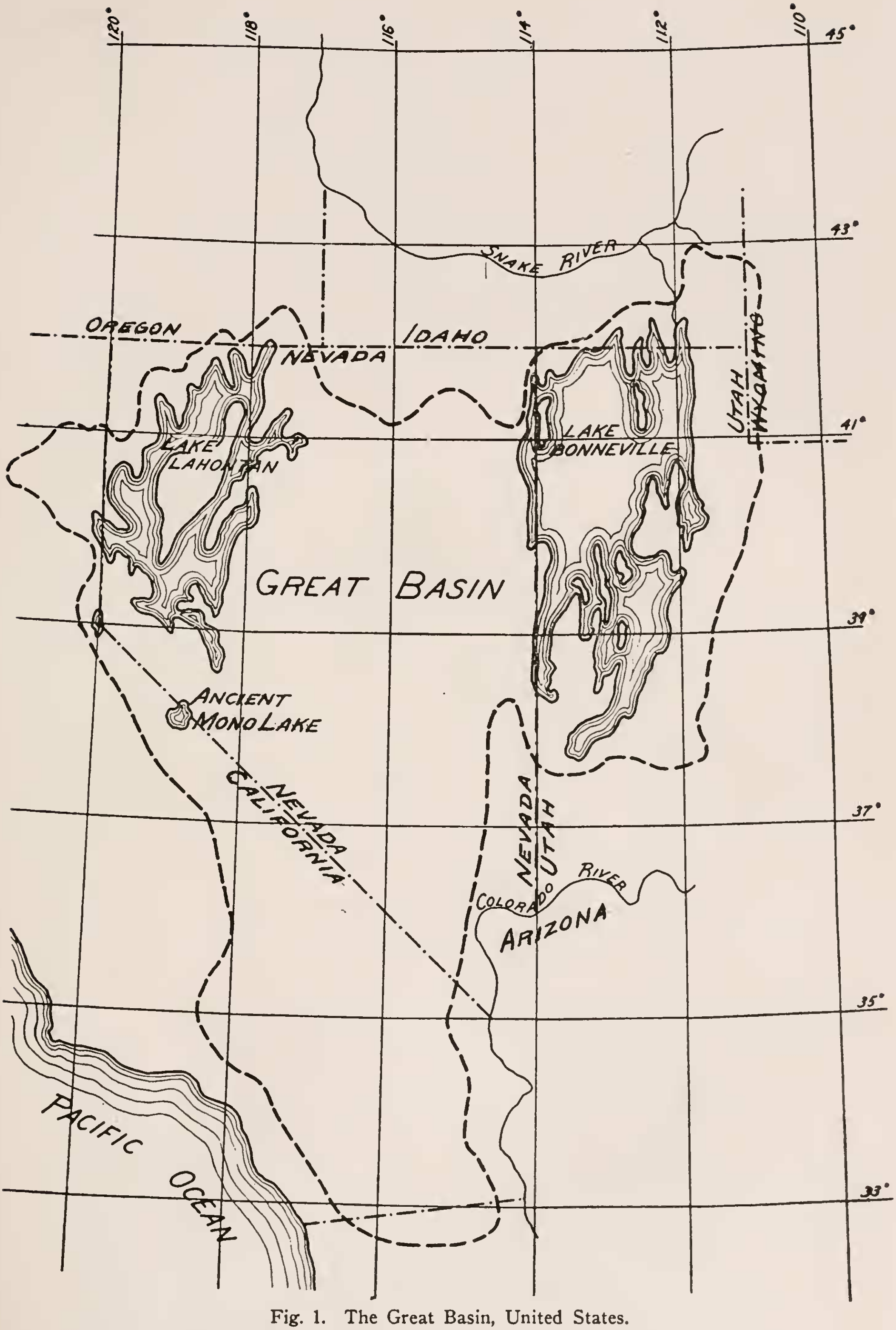

Fig. 1. The Great Basin, United States.

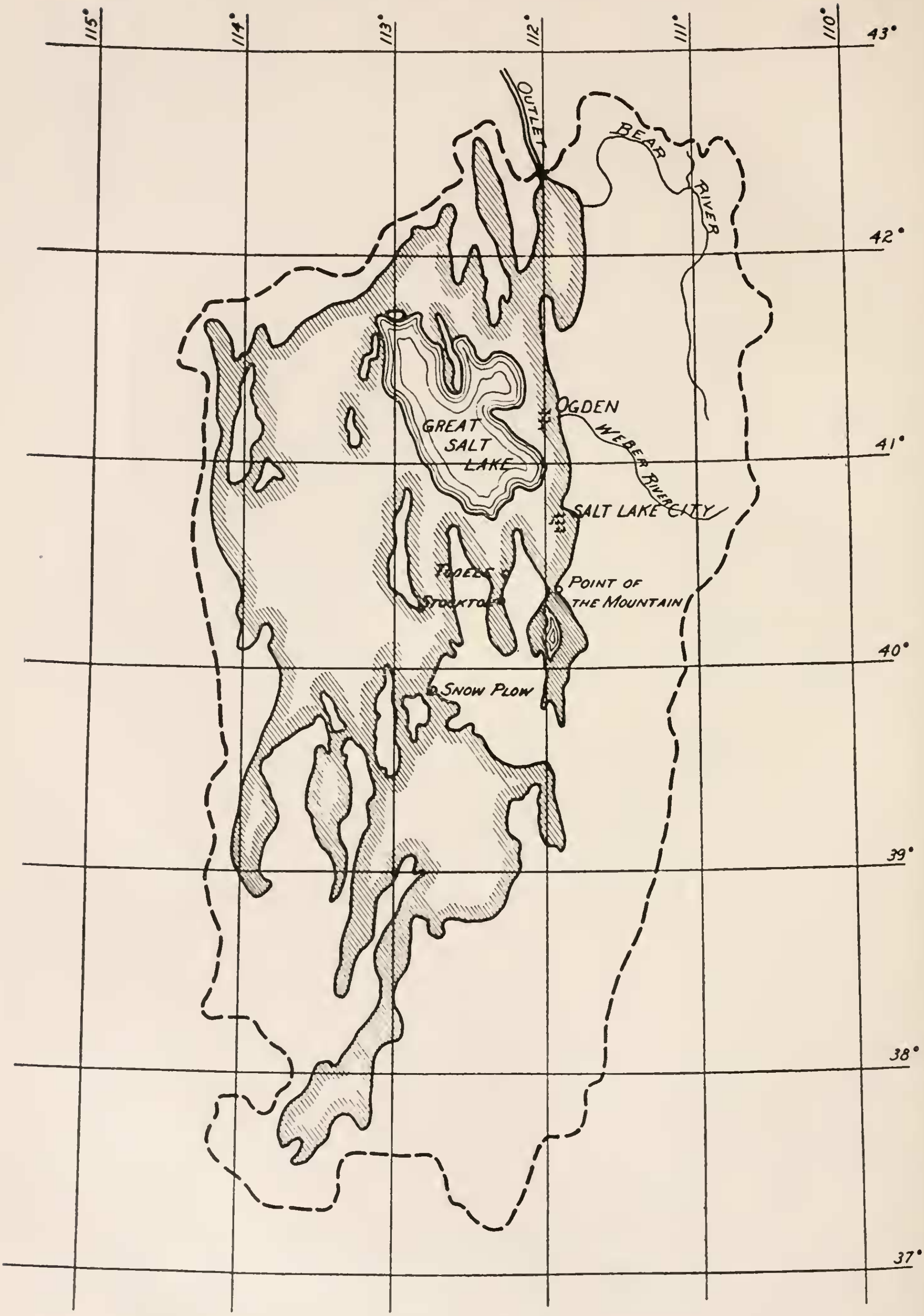

Fig. 2. Lake Bonneville, Utah.

ville; its depth was nearly as great. Lake Lahontan had no outlet.

Ancient Mono Lake is the third of the Quaternary lakes, already referred to. This lake on the plateau at the eastern base of the Sierra Nevada had in Quaternary times a maximum surface extent of 316 square miles or four times that of the present Mono Lake. The surface of the ancient lake was about 680 feet above the present lake level. The ancient Mono Lake had no outlet. All of the water which fell upon the lake and upon the surrounding mountain slopes, as rain or snow, went back into the air by evaporation.

The physical facts of immediate interest relating to these Quaternary or Pleistocene lakes as taken from the reports of Dr. Gilbert and Mr. Russell in Monographs I and XI of the U. S. Geological Survey are as follow:

The greatest extent of Lake Bonneville was 19,750 square miles. Its highest stage was 1,000 feet above the present surface of the Great Salt Lake. Its drainage basin, coincident with that of the present lake, is 54,000 square miles in area. The outlet of the lake was at the north into the valley of Snake River. There was no outflow after the lake had fallen below the level of the Provo beach at about elevation 630 feet higher than the present lake. The area of the present lake is about 2500 square miles. (See Fig. 2.)

The greatest extent of Lake Lahontan was 8422 square miles. The drainage basin in which this lake appeared has an area of about 40,000 square miles. The lake's average depth was about 500 feet. Its greatest depth 886 feet. (See Fig. 3.)

The greatest surface extent of ancient Lake Mono was 316 square miles. Its water surface was about 680 feet above that of the present lake. The present lake has a water area of about 85 square miles. Its drainage basin has an area of 973 square miles. (See Fig. 4.)

Of Lake Agassiz we are told by Warren Upham of the U. S. Geological Survey, that its surface extent was 110,000

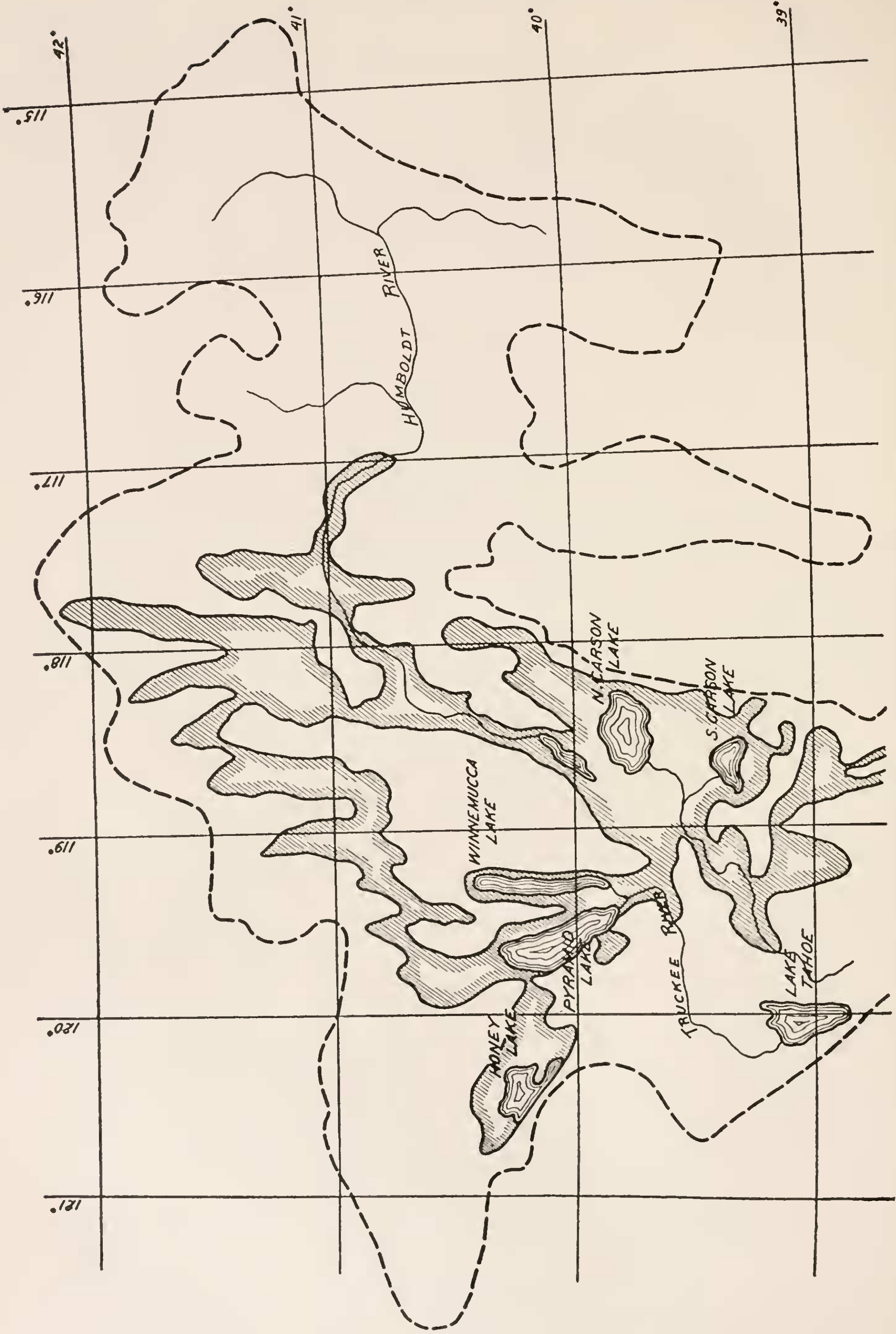

Fig. 3. Lake Lahontan, Nevada.

square miles, its tributary watershed 350,000 to 500,000 square miles and its water surface elevation about 700 feet above the present surface of Lake Winnipeg.

The existence of these Pleistocene lakes, particularly of those which had no outlets, affords a convenient means for estimating the rainfall in their watersheds in the Quaternary epoch. The great extent of these lakes may be accepted as evidence that the rainfall was then far greater than in our day. It may be assumed that temperature did not differ greatly from the present, though somewhat warmer. The loss of water by evaporation from an open body of water from lakes and from the ocean was, therefore, probably materially greater in a given period of time than today. Assuming, however, for purposes of a first approximation that evaporation losses from the interior lakes was the same as at present, then by a simple calculation a determination can be made of the increased precipitation that would have been required to maintain the two land-locked lakes at their full stages.

This analysis indicates that the precipitation throughout the drainage basins of each of the two landlocked lakes must have been about twice as great, when they were at their greatest extent, as it now is. A similar calculation shows the same relation to present day rain, of the rainfall on Lake Bonneville when it had its greatest extent and before it broke its barrier to the north. After the outlet began to discharge Lake Bonneville water into Snake River, the rainfall may have been, relatively, still greater. There is no means of telling.

If the conjecture be correct that the weather was somewhat warmer in Quaternary times than now, then evaporation from the Quaternary lakes must have exceeded that of the present time and this excess, too, must have been made up by more rain. The assumption, therefore, that there was twice as much rain and snow in the plateau region of the continent in Quaternary times, than now falls there, does not seem unreasonable. It is probably an underestimate.

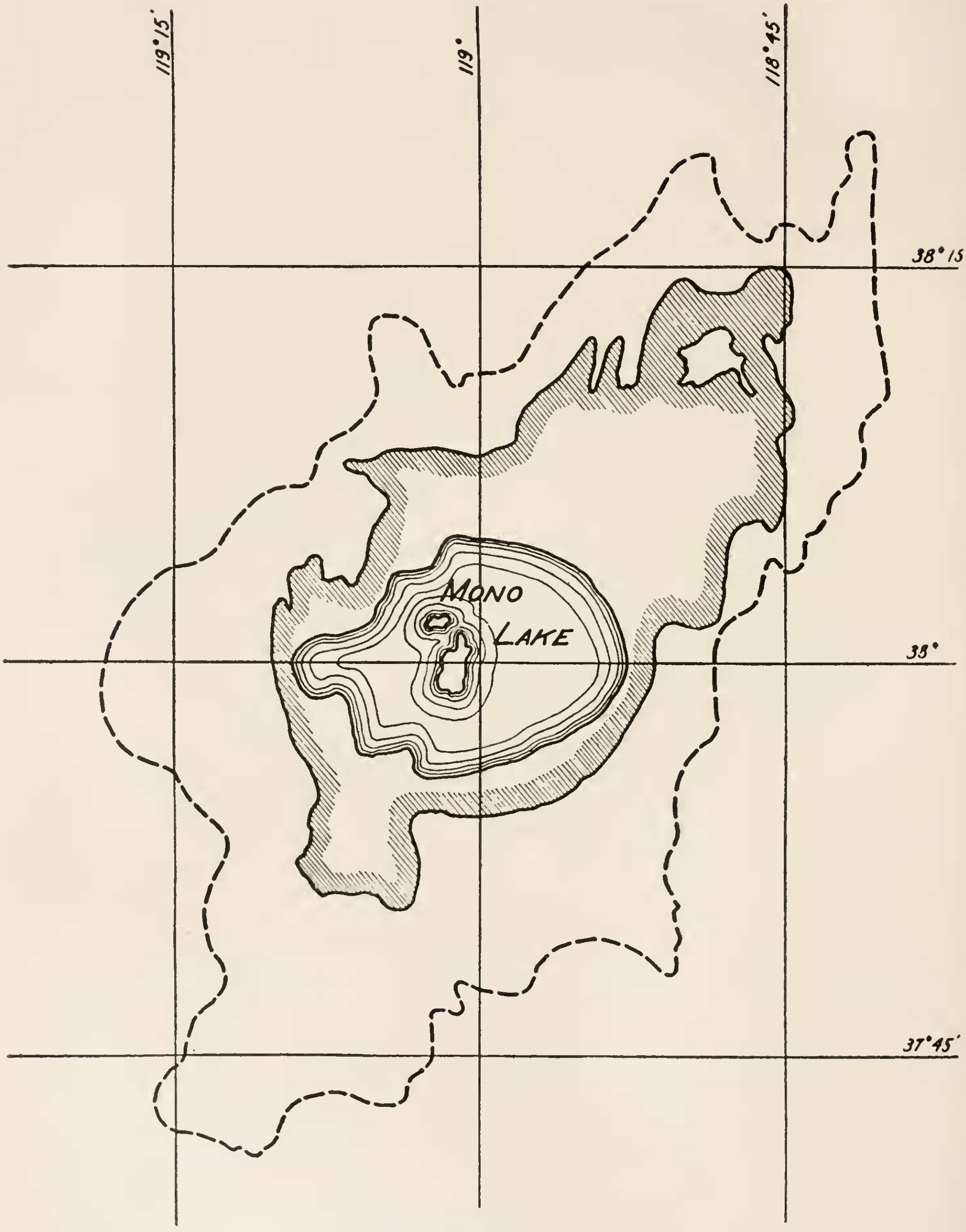

Fig. 4. Ancient Mono Lake, California.

But if there was twice as much, or more, precipitation to the east of the Sierra Nevada, there must have been a similarly greater precipitation than at present on its crest and on its western slope. The normal precipitation throughout that portion of the Sierra Nevada which is known to have been covered with glacial ice—contemporaneously with the existence of the Quaternary lakes—now ranges from about 40 to above 90 inches per annum of rain equivalent. Most of the precipitation is in the form of snow. If this precipitation were doubled the annual snow fall at the high altitudes would exceed the annual depletion by melting and by evaporation and there would be an extension of glaciers down into the greater warmth of lower altitudes.

Exactly this occurred in Quaternary times. It will thus be seen that a warm climate of the period, conducive to the rapid transfer of moisture from the ocean to the atmosphere and back again to earth as rain or snow would account not alone for the large rivers and the great lakes of the plateau region but also for great local accumulations of ice in the concurrent Glacial Period, as in our own northern latitudes.

That, elsewhere, too, rainfall was heavy at this period of the earth's geologic history is a well-known fact, thus for example L. Larter (in Comptes Rendus de l'Academie des Sciences in 1856) shows that the Dead Sea in late Tertiary or Quaternary times must have had a considerably greater extent than at present, as evidenced by sediments deposited over enormous stretches of country both to the north and south of the present lake. He correlates the existence of this ancient lake with the Glacial Epoch, evidences of which in this region are found in the moraines on Mount Lebanon. The ancient Dead Sea had a water surface about 1300 feet higher than the present lake.

It is worthy of note that evaporation rates have, heretofore, generally been over-estimated, and a few words, therefore, on this subject may not be out of place. The geologists of the U. S. Geological Survey have generally assumed an evaporation rate of 6 feet or more per annum in the plateau region. This is from two to three times greater than more recent information on this subject would indicate. Numerous observations have shown that fairly close estimates of the yearly evaporation from open bodies of water can be made in regions whose mean monthly air temperature is known. Temperature is the dominant factor influencing the rate of evaporation. It follows that altitude, because temperature decreases with altitude, is to be taken into account when evaporation is to be approximated in regions where experimental observations are lacking. To illustrate—in temperate regions such as in the great valley of California, at sea level, evaporation from a large open body of water is about 4 feet per annum. At Lake Tahoe at an altitude a little over 6000 feet the rate is about 20 to 24 inches per annum. (Note. Evaporation from a pan floating in shoal, and therefore comparatively warm water on the western shore of the lake has been found by measurement to be about 30 inches. This is certainly in excess of actual evaporation from the entire lake surface). Using mean monthly temperatures at Truckee, and the evaporation rates indicated by the Kingsburg curve (See Trans. Am. Soc. C. E. Vol. LXXX, page 1978) evaporation in the Tahoe region at altitudes of about 6000 feet should be about 17 inches per annum.

At the Great Salt Lake, elevation 4200 feet, evaporation takes place at the average rate of about 30 inches per annum. The lake receives only a relatively small accession of water from July 1 to October 1. During this period of three months the average drop of the lake's surface has been 1.2 feet in the 21 years, 1903 to 1923. In these three months the rainfall on the lake has averaged 1.3 inches. The accession of water to the lake from underground sources is known to be small. This is evidenced by the occasional large monthly drop of the water surface, due to unusual warm weather which allows no place for an assumption of material accession of water from underneath. The visible or surface inflow, during these months, is also very small. Allowing, however, a small amount for accessions of water other than by direct rainfall, the aggregate accession may be called 2 inches or 0.17 feet. (This is equivalent to a continuous inflow of 133 sec. ft.) Evaporation during these three months must therefore have been about 1.37 ft. (1.20 +0.17=1.37). But with the aid of mean monthly temperature records it is found that in the Salt Lake region the evaporation in the three months under consideration is about 60 per cent. of the annual evaporation. Consequently 2.3 feet, or 28 inches, is indicated as the average annual evaporation rate. It is preferred to call this about 30 inches or 2.5 feet, which as already stated, is less than one-half of the amount of evaporation per annum usually assigned by geologists to this plateau region.

There were great rivers in the epochs preceding and following the Ice Age and no doubt during the same. These were the result of large runoff caused by heavy precipitation. The shrinking of the glacier, extending, we must assume over thousands of years, contributed so little water to the runoff that this factor is negligible as affecting the stream flow of post glacial times. The annual melt and the shrinkage are not, in other words, to be confounded.

Preceding the filling of Lakes Bonneville and Lahontan and Mono Basin with water in Quaternary times, there appears to have been a period, generally referred to as a period of desiccation, during which cones of alluvial material were deposited at the mountain bases of the valleys. It is quite probable that this period was not as dry as might be supposed. The alluvial material required water for its transport but this water was evaporated probably under the influence of high earth and air temperature even as at so many other spots on the globe where the thick deposits of salt are mute evidence of the evaporation of vast bodies of water.

The great salt deposits as we know them in parts of the Old World, in central New York, and in the South, represent the evaporation of tremendous quantities of ocean water. Of those in New York State it is said that the quantity of water that must have been there evaporated was equivalent to a layer a mile in depth. Here, as in the case of the salt deposits of Europe, there was probably a land-locked arm of the ocean full of water at a relatively high temperature, being evaporated, perhaps with earth heat, at a rate faster than freshwater flowed in from the surrounding drainage basin.

There is a constant flow into the Mediterranean Sea through the Straits of Gibraltar. Tributary rivers do not fully replenish evaporation losses. Its water therefore contains more salt than ocean water—about one-sixth more. In contrast with the Mediterranean Sea the waters of the Baltic Sea contain less salt than the ocean. The present-day accession of freshwater from tributary watersheds exceeds the evaporation. This condition was, as geologists tell us, less pronounced in an earlier geologic time. The water was then much saltier, quite likely due to greater evaporation resulting from warmth from underneath.

At many places on the globe a saturated brine was produced in land-locked bays and precipitation of the salt took place. How long it took to produce the known deposits which in New York State are 60 to 75 feet and which in parts of Europe as shown by deep borings, are 3000 feet and more in thickness, must be left to conjecture. The rate may have been rapid or very slow.

An extreme condition in the latter sense would be similar to that represented in our day by the Mediterranean Sea where nearly as much freshwater is annually delivered to the sea as evaporated from its surface with the result that its salinity is only slightly in excess of that of the ocean and apparently has changed but little through the centuries.

No better illustration than the world's great salt deposits is wanted of effects that have resulted from the hot condition of the earth's crust at the close of the Silurian age when these deposits were formed. At this time, moreover and in the epochs which followed, the climate was from temperate to torrid the world over, except only as modified by altitude.

When the cooling of the globe had progressed so far that in some places the winter precipitation was snow and not rain, and this snow fell upon a land surface sufficiently cool, it began to accumulate. Despite the general warmth of the climate, which I venture to suggest must have continued throughout the Glacial period, the volume of snow which fell was in many places greater during the colder winter months than the heat of the following summer could melt. The snow began to pile up and the glacier began to form. Such a place on our own continent was the region between Montreal and Hudson Bay.

The southward advance of the North American ice sheet was not from the polar region. The ice accumulated at points of large snow precipitation and radiated from these points, notably from the point to the southwestward of Hudson Bay, in all directions. The ice flow and the extent of the glaciers must have been determined by the relation of the annual snow fall to the annual rate of snow melting. The glaciers continued to grow in extent in all directions and in thickness so long as the snow fall predominated; they commenced to shrink when there was more melting of the ice than snow replenishment.

The annual snow deposit at the beginning of the Glacial Epoch when the great North American glacier began to form slightly exceeded the rate of melting and evaporation, with the result that the ice fields which it formed were gradually extended toward the north, south, east and west until in due time the entire northern portion of the continent was an ice sheet with a greatest thickness of at least 10,000 feet and perhaps much more. Where this ice sheet covered the ground it was of course cold, particularly in winter, but speaking in a broad sense, the earth's climate all around the ice was temperate or warmer than temperate; this was the condition even in the Arctic region, toward which, as toward the south, there was a flow of the ice. This flow apparently emanated from the region where the ice field attained greatest thickness.

For any other satisfactory explanation of the accumulation of the ice than a generally warm climate with much rain and snow, we seek in vain. Many geologists, as already noted, assume that the earth passed through a period of low temperature and try to account for the same. And, then, in considering the obvious explanation, they are confused by the fact that glaciers existed in Cambrian and Permian times as well as in Quaternary. This should not be disturbing, because during all these periods much of the ocean, if not all of it, was warm and evaporation was large with consequent heavy precipitation and with large streamflow in some places and large accumulation of snow in others. It would take but slight changes in the direction of ocean currents and in elevation, many of which are known to have occurred, to change the places of heaviest precipitation and even to produce an ice field where, without change of general climate there had been none before.

Broadly speaking, the period of heavy but gradually decreasing rainfall must have continued until the ocean had cooled to near its present temperature. The decrease of precipitation considered in the aggregate over the entire surface of the globe, though gradually approaching that of our day, was still sufficient in Quaternary times to supply water to great river systems, and to supply more snow to vast continental areas than rains and solar energy could reduce to water. It was later, perhaps, that the effect of earth heat upon the rate of evaporation became negligible as a factor and the fall of rain and snow was correspondingly reduced. The melting of ice began to exceed replenishment by snowfall, and the shrinking of the ice field commenced. This shrinking did not, as already stated, cause the great post glacial floods of which there is abundant evidence. Melting was a slow process even as the forming of the glaciers had been slow. It is, moreover, a process going on even in our own day to a measurable extent without notable effect on the flood-flow of glacial streams. The retreat of the glaciers of Switzerland is an historic fact, as also that of the glaciers of Alaska. They will never again advance unless, indeed, there be such shifting of ocean currents and of storm tracks or changes in altitude as will materially affect local precipitation to the advantage of the glacier.

According to the conception of the Ice Age as occurring during a period when the climate was warm, during a period when the earth's temperature at the poles was still sufficiently high to maintain conditions as we now know them in temperate or semi-tropical zones, the Ice Age most probably fell into that period of geologic time in which the influence of earth temperature upon the temperature of the ocean was dwindling. It is because of this fact, if it be a fact, that no recurrence of the Ice Age is to be looked for. The advance of the ice, its retreat and readvance all fell into one geologic epoch, controlled by terrestrial influences as already suggested.

From the exhautive studies of the late Dr. G. K. Gilbert, we learn with reference to Lake Bonneville that before the great flooding, the water-level was low and that this pre-Bonneville period was of great duration compared with those that have followed. A first Bonneville high-water appears to have been followed by a period of near or complete desiccation. Then came a second period of high water, the waters rising until overflow was reached. Subsidence followed down to the level of the Provo Beach, 370 feet below the highest lake stage and there, there was a long halt. Then came the further recession to the existing condition.

Geologist Russell finds evidence in the Mono Lake basin to substantiate Dr. Gilbert's conclusion that these Quaternary lakes had two successive high stages, a fact which, if accepted, would be in substantiation of the claim that there were at least two successive advances of the ice sheet; that there was a fairly long interglacial period.

Concerning such an interglacial period, W. B. Wright in his Quaternary Ice Age (p. 171) remarks that "Opinion is by no means undivided as to the interglacial significance of these beds" (the Toronto formation)."It is generally admitted that they must have been formed during a temporary retreat of the ice from the immediate neighborhood of the sections, but there is the usual disagreement as to the extent of the retreat."

Referring to the same Toronto Formation, Mr. G. W. Lampaugh in an address in 1906 before the Geological Section of the British Association, said: "On this and other evidence it is clear that during the course of the Glacial period the whole of the district was for a considerable time released from the ice sheets which previously and afterwards covered it. Moreover, in the opinion of Professor Coleman" (A. P. Coleman who first described the interglacial Toronto Formation), "Some of the plants and shells of the warm climate beds denote conditions which would be incompatible with the persistence of the ice sheets anywhere in Canada; and if this be so, then we here have proof for at least one interglacial epoch. But I still permit myself to feel doubt regarding this last mentioned deduction, as the shells and plants in question, which have their present habitat in the Middle United States, even yet endure winters of considerable severity; and there are certain factors in the composition of the beds and their altitude above Lake Ontario that justify caution."

G. F. Wright in "The Ice Age of North America," sets forth reasons for regarding the period as a unity but he says (page 195): "On any view of the case we are compelled to regard the Glacial period as one of great vicissitudes. Evidently . . . . there were great irregularities both in the advance and in the retreat of the ice. From a combination of causes which can not yet be explained there were periods of rapid advance alternating with periods of retreat, intercalated with long periods of equilibrium. The glacialist possesses the great advantage of having a most complicated cause at hand to account for his phenomena. But while this enables him to explain everything, it as well prevents him from being over-confident in any special solution he may present of minute problems."

Not only does it appear that the rainfall and snowfall in Quaternary times must have been twice that of the present time, or more, but our Pleistocene lakes have left good evidences to show which way the wind blew.

A recent visit to the Point of the Mountain (See Plate 1), some 30 miles south of Salt Lake City and an inspection of the Bonneville Beach gravel deposit at that point led to some speculation as to how this large deposit was made. It is not a detrital alluvial cone in the ordinary sense. There is no break in the mountain range through which the gravel could have been brought by a creek or river into the main valley. The gravel must have been moved along shore until it found its resting place. Water actuated by wind was the transportation agency. It appears clear that while Lake Bonneville stood for thousands of years at the level marked by this beach formation, the prevailing winds were not unlike those of today. The summer winds were from the north or slightly northwest, the winter brought the strong blows from the south.

Each ravine descending from the bordering mountain range contributed some gravel to that formed by wave action at the base of the ancient sea cliffs. On this long extent of north and south beach to the northward of the Point of the Mountain this gravel was shifted about by wave action. The direction of the beach was slightly south of west turning at a pronounced spur, against which the great gravel spit now rests, abruptly to a southeasterly direction. The waves driven by the northerly wind during the summer months picked up the surface layer of gravel particles and rolled them obliquely up the beach in a southerly or southeasterly direction and under the influence of the return flow of the water which was left on the beach by each succeeding wave they then rolled down again, but in a direction normal to the direction of the beach. Each such displacement took them a little further south on the beach, a little closer to the Point of the Mountain. At this point the waves from the north, running there at right angles to the shore line, lost their power to transport the gravel lengthwise of the beach and the gravel came to rest. Not only was this the case but the winds from the south which in winter sent waves against the shore southward from the Point of the Mountain caused a similar creep of shore gravels toward the north, and their influence in this direction, too, stopped at this point. No other causes were needed to accomplish the building of the gravel spit.

Referring to a similar deposit of gravel on the same old Bonneville Lake shore at the pass between the Tooele and Rust valleys, where a spit of gravel projects westerly having a length of about 7000 feet and a height at its extremity of 150 feet, Dr. Gilbert says: "The greatest waves came from the north, and beating on the southeast shore of Tooele Bay, carved out a long line of sea cliffs." Dr. Gilbert speaks of the waves and undertow and a littoral current as the agencies which contributed to a southward transport of the resulting gravel. The assumption of the littoral current is superfluous, it probably did not exist, certainly not of force sufficient to transport gravel. At lower stages of the lake still more gravel was added to this great gravel bar, usually referred to as the Great Bar near Stockton. Here as at the Point of the Mountain, there is clear evidence of persistent strong winds from the north—no doubt the spring and summer winds and of wind, too, from the south—the winter winds.

All the available evidence appears to indicate that during the Glacial Age the climate in general and particularly in the polar regions was similar to that at present in the temperate zones. There were, no doubt, at that time certain regions in which earth heat still had a strong effect on surface temperature and particularly upon the temperature of ocean water. Such a point of influence may have existed in the North Pacific, where even today our storms appear to originate and possibly, too, in the North Atlantic. Accelerated evaporation, due to earth heat and relatively high temperature, loaded the air with the vapors which fall as snow in the north of Europe and which in the north of our own continent produced the glaciers.

It is quite conceivable that as cooling progressed and evaporation decreased, both the continental ice sheets and the Quaternary lakes began to shrink, in each case due to lack of snow and rain, and that later activity of the plastic mass under the crust of the earth resulted in a belated local rewarming of ocean waters and of a second period of heavy precipitation with partial restoration of the ice sheet and a complete refilling of the Quaternary lakes.

Though he doubts somewhat the importance of precipitation as a factor controlling the extent of ice fields, some light is thrown on this subject by W. B. Wright of the Geological Survey of Ireland in his work on "The Quaternary Ice Age." He says (page 450): "There has of recent years, been a tendency among geologists to exaggerate the importance of precipitation in the production of glaciers and ice sheets" . . . . "The really essential thing" he says "is the lowering of the snow line so as to bring some portion of the range into the region of perpetual snow." But he continues: "This nevertheless does not make the matter perfectly clear, for the height of the snow line, although mainly a matter of temperature is to a certain extent, dependent on precipitation. Thus, in the west of the Alps, and in the extreme southeast, near the Adriatic, where the precipitation is greatest, the present snow line is relatively depressed."

Again quoting Dr. Gilbert: "To account for the origin of Bonneville Lake, we need to assume a climatal change that would increase precipitation or diminish evaporation; and both of these effects would follow, in accordance with familiar meteorological laws if the humidity of the air were increased, or if the temperature were lowered."

Dr. Gilbert seems, however, to have failed to consider the possibility of increased precipitation outweighing the local effect of increased evaporation that would take place under the influence of a warmer climate.

Several facts may be cited to show occasional long time persistence of weather types. Thus, for example, some 60 years ago, Goose Lake in the extreme northeastern portion of California, extending over the boundary line into Oregon, contained enough water to overflow. The rainfall since that time, however, has not been sufficient to offset the evaporation from the lake and it has been shrinking. The same is true, though less obviously in the case of Tulare Lake whose bed has repeatedly been dry since 1898 but which had been overflowing from 1862 to 1876. In the case of Tulare Lake it is known that at some remote date, historically and not geologically speaking, the lake had been very low—far below the overflow level, almost desiccated in fact, for a period long enough to permit willow trees to take root some 17 feet below the lake's high water level and grow to diameters of 4 feet and more. These facts show the occasional persistence of comparatively light rainfall for long time periods, for half centuries and possibly for centuries, followed by other long periods with more precipitation. In the case of the Great Salt Lake similar variations in the amount of precipitation for series of years is to be noted. This is clearly evidenced by the known fluctuations of lake levels. This lake was low in the 40's, continuing so until about 1860. It then rose from year to year to a stage about 10 feet higher culminating in 1870 and holding the high stage for seven or eight years. There was thereupon a drop to a second low stage in the 90's at which time the consensus of opinion seems to have been that the lake would feel the effect of diversions of water from its tributary rivers for irrigation and would never again rise to a high stage. The lake, however, responding to the effect of somewhat larger precipitation began to rise again and has now for several years been at or near the high stage of 50 years ago. No regularity of any kind is indicated for the alternative periods of lows and highs—of persistent light rainfall and of persistent heavier rainfall.

Bearing on this matter and to show that causes for local changes in climate are not difficult to find, Prof. C. H. Hitchcock might be cited as shown by the following taken from Warren Upham's Monograph on "The Glacial Lake Agassiz": "The general absence of Pliocene formations along both the Atlantic and Pacific Coasts of North America indicates, as pointed out by Prof. C. H. Hitchcock, that during this long period all of the continent north of the Gulf of Mexico held a greater altitude, which from the evidence of these submarine valleys is known to have culminated in an elevation at least 3000 feet higher than that of the present time. Such plateau-like uplift of the continent appears to have exerted so great influence on its meteorological conditions, bringing a cooler climate throughout the year, that it finally became enveloped by ice sheets." . . . . "The thickness of the ice in the region of the White Mountains and Adirondacks was about 1 mile; and Dana has shown from the directions of striations and transportation of drift that its central portion over the Laurentide highlands between Montreal and Hudson Bay had, probably, a thickness of fully 2 miles."

In discussing climates, as already stated, we are too apt to compare mean annual temperatures with each other, regardless of variation in extremes, forgetting that a difference of a few degrees in the warmer months of summer counts for very much more than the same difference in winter months at a temperature below the freezing point. Thus, for example, in the matter of temperature influence on evaporation: When the mean monthly temperature is below the freezing point the evaporation from open water, or from snow and ice surfaces, is very light. Consequently no drop in temperature even to many degrees below zero of our Fahrenheit scale can affect the amount of evaporation in any given time to any great extent. Changes of 20° or even of 40° in the mean monthly temperature of the winter months of our northern latitudes would affect the aggregate annual evaporation but little. On the other hand a change of a single degree Fahr. in the mean temperature of a single month will add to the monthly evaporation from 0.1 inch to 0.3 inch according to whether the mean monthly temperature is in the neighborhood of 40° or in the neighborhood of 80°. In its influence on meteorological conditions, and especially on evaporation a few degrees of change in the mean temperature of summer months, then, will outweigh the influence of any possible change in mean monthly temperature of winter months particularly if the winter temperatures are below the freezing point. Where winters are cold the mean annual temperatures are, therefore, of but little moment in a discussion of the weather conditions which affect the persistence of ice or of land-locked bodies of water throughout a series of years. It is the temperature of the warmer months of the year which counts. If a summer month has a temperature 10° in excess of a normal of 70° the evaporation during such an unusually hot month will exceed normal evaporation by nearly 3 inches. (Evaporation from a large open body of water is here meant—not evaporation from experimental pans, in which there is always an accellerated rate.) And if such a departure of temperature from normal should persist throughout an entire summer season the consequent departure of evaporation from normal in the year might easily reach 10 to 20 inches of excess, even though the departure of temperature in summer be offset many times over by excessive cold in the winter months.

In our temperate latitude, departure from the mean monthly temperature in the amount of 10° is not common nor is such a departure likely to extend to all the warm months of any single season. But when we go back in geologic time to an earlier period, to a period even as recent as the Quaternary, it takes no great stretch of the imagination to conceive of a climate a few degrees warmer in summer than that of our time. It must have been so, if there is any merit in our conception of the gradual cooling of our globe.

The greater warmth sent greater volumes of water into the air from wet ground, lakes and oceans and, as all of the water rising as vapor must fall to earth again, there was a corresponding increase of aggregate precipitation. It is readily conceivable that there was sufficient concentration of this excess, on our Sierra Nevada and east thereof and, too, in the region of the great ice fields of the north to maintain our local Sierra Nevada glaciers and the Pleistocine lakes, and the great glaciers of the Ice Age.

The climate of the Ice Age was, then, characterized by greater warmth and not by greater cold than in our day. This, of course, does not mean that the presence of the ice and the heat consumed in its melting did not have some local effect upon temperature of the atmosphere and, therefore, upon climate.

Evaporation from ice and snow is relatively very light. The melting of the glacial ice, too, is slow at the low temperatures which prevail in a region of glaciers. Furthermore, the greater differential in heat content of the air over the warm ocean and over a great adjacent ice field must have been conducive to cloudiness and consequently a shielding of the ice field from the direct rays of the sun. The ice may be conceived as having caused local low temperatures, rather than that cold was the cause of the Ice Age.

High ocean temperature and disposition of land and water favorable to heavy precipitation in the northern hemisphere together with some changes in altitude[1], probably quite moderate, and a somewhat warmer climate, would appear sufficient to explain the Ice Age. Lower mean temperature of the globe than at present could not have existed, though temperatures may have been lower in some localities. A generally cold climate with lesser evaporation and consequent lesser precipitation would not necessarily result in the growth of glaciers. Heat with large evaporation, and heavy precipitation will fully account for the vast accumulations of snow and ice in favored localities. The Ice Age fell, we may assume into that period at which the earth's crust had cooled to near present day temperatures but during which the ocean was still receiving heat from below, in spots at least, causing convection and probably ocean currents much more pronounced than those of our day in which ocean water is warmed to a slight depth only by the heat from the sun.

The two great centers of atmospheric depression, the regions in which the great cyclones originate, which bring rain, are near Greenland and near the Aleutian Islands.

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[1] Changes in altitude were caused, in large part, no doubt, by the gradual shifting of the vapor load from the land areas to the ocean during the time that the temperature at surface of the Earth dropt from the critical temperature of water (365° C) down to that of the present time. A great load was thus removed from the land areas, as the vapor condensed and flowed into the ocean. On the basis of the relative extent of land and water areas the shifting of the water load must have been equivalent to a removal of about 6000 feet in depth of water from land areas and the addition of about 2000 feet in depth to the ocean.

On the assumption that these same centers of barometric lows existed in the Ice Age and that the paths of the storms were substantially the same as today but that storms were of greater extent and dropped more rain and snow, the localization of the great ice sheets in the northern part of our own continent and in the northwestern part of the Eastern continent could be fully explained. There were no glaciers in northern Asia because the air had lost its surcharge of moisture before it got that far.

Some geologists are not satisfied with a single interglacial epoch but contend for a number of such epochs—up to six or perhaps even more. Changes in the distribution of rainfall due to local causes such as modifications of ocean currents or the formation of new mountain ranges, would amply account for such breaks in the continuity of the Ice Age.

Because changing extent of land areas and moderate changes in elevation will readily account for local variations in the amount of snowfall there must have been many places in past geologic times where conditions were favorable to the formation of glaciers. Some evidence of glacial action is, therefore, to be expected far back in geologic history. The glacier, in other words, resulted from the same general prime cause as the great river systems of the past. It is only, however, in such places as the Dead Sea and as in our own Quaternary Lakes that we note a clear correlation of ample water production and its accumulation in land-locked basins, with the presence of glaciers.

Russell reaches the definite conclusion that the greatest expansion of Lakes Mono, Lahontan and Bonneville was contemporaneous with the maximum extension of the North American ice sheet. He says "The last great expansion of the lakes of the Great Basin occurred during the close of the Glacial period, and may be considered as contemporaneous with the Champlain epoch of the Eastern States."

The interglacial epochs whether one only, or a number, as contended for by many geologists, are almost invariably referred to as periods of warmth. This conception is reasonable but implies a conception of the Ice Age as a period of cold. I venture to believe that, except as locally modified by the presence of ice, the entire Ice Age together with its interglacial period was a period of warmth, a period of large evaporation from open bodies of water and in consequence a period of heavy precipitation making for large stream flow and for large snow fields.

I have ventured in the foregoing to question the generally accepted conception of the earth having passed through any period of cold. I have pointed out that the land-locked Pleistocene lakes, Ancient Mono, Lahontan and Bonneville, afford means of approximating precipitation in relation to that of today; that this precipitation was probably twice as great; that heat with consequent large evaporation was necessary to produce this heavy precipitation, and that because the existence of these lakes was contemporaneous with the Ice Age, the accumulation of snow must also have been due to heavy precipitation. The climate of the Ice Age, generally speaking, must therefore have been warm, warmth being necessary to account for heavy precipitation. Diversity of climate then, as now, is clearly indicated by the records as they have been interpreted by geologists although in this and earlier geologic times the influence of latitude, owing to more widely distributed earth heat, was probably somewhat less than now.

Periodic changes in the extent of the ice fields and of the Pleistocene Lakes can be fully accounted for by changes occurring from time to time in continental outlines and elevation of landmasses with resultant changes in ocean currents. There is then no need of assuming an era of cold as the cause of the Ice Age. Where the climate was locally colder than it now is, the presence of the ice was the cause and not the result of the cold.